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Simulations investigating the effect of a deuterium-tritium-ice coating on the motion of the gold cone surface in a re-entrant cone-guided fast ignition inertial confinement fusion capsule

J. Pasley
University of California San Diego, 9500 Gilman Drive, La Jolla, California 92093-0417

R. Stephens
General Atomics, 3550 General Atomics Court, San Diego, California 92121-1122

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One- and two-dimensional multigroup radiation hydrodynamics simulations have been performed to investigate the motion of the gold plasma generated at the surface of the embedded gold cone in a re-entrant cone-guided inertial confinement fusion capsule. The effect of deuterium-tritium (DT) ice layers, and other possible tampers, of varying thickness, upon the motion of the gold cone plasma has been investigated. The effect of the x-ray drive spectrum incident upon the ice layer is also explored. Ice is shown to tamp the expansion of the gold cone, and whilst denser materials are shown to be more effective in this role, ice does not pollute the ignition region with intermediate-*Z* ions, which, though preferable to gold contamination, also tend to inhibit the attainment of high fuel-ion temperatures. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2734584]

Much recent work on fast ignition (FI)[1] for inertial confinement fusion (ICF)[2] has involved the use of capsules in which a re-entrant gold cone has been embedded.[3] As in the original scheme described in Ref. 1, the re-entrant cone-guided FI scheme employs a laser pulse with power on the order of 10 PW and energy of around 100 kJ to heat a region of approximately 1000× compressed equimolar deuterium-tritium fuel, which satisfies the ρr criteria for ignition, to the multi-keV temperatures required for alpha-particle bootstrapping and subsequent propagating burn. Here, the igniter laser pulse is incident on the interior of the gold cone, which is embedded in the capsule such that the cone tip is directed toward, and located within approximately 100 μm of the assembled dense fuel core. The object of this cone interface being to avoid the requirement that either the igniter pulse, or a less intense "hole-boring" pulse, first channel through some few millimeters of plasma, such as would ordinarily surround the core formed from the uniform spherical implosion of a fuel shell.

Experimental studies of cone guided FI have, to date, employed deuterated plastic fuel shells.[4] However, it is likely that ignition scale designs would be cryogenic and this seems to be a necessity for high-yield experiments. In this regard, there are a number of interesting open questions concerning the presence and behavior of DT ice on the outer surface of the gold cone where this surface lies inside the capsule. To date, the ice layers in cryotargets are formed, just below the critical temperature, by beta layering,[5] in which the energy deposited by tritium's beta decay creates a temperature gradient between the inside ice surface and the outside of the shell and forms, by vapor transport over the inside surface, a uniformly thick ice layer on the inside of the spherical shell. The insertion of a re-entrant cone complicates the geometry; however, if measures are not taken to prevent it, one would expect the ice layer to extend over the surface of the cone. This situation is illustrated in Fig. 1.

Previous simulations of re-entrant cone-guided FI capsule implosions (for example, Refs. 6 and 7) have typically not included a layer of DT ice on the cone, largely for the reason that actual targets have, to date, been noncryogenic in nature. It is also the case, however, that simplification of this region has some computational advantages due to the difficulty of modeling the shear flow at the interface between the imploding capsule and the cone with a Lagrangian computational mesh, so the tendency has been to omit the ice on cone layer even when performing more speculative modeling of cryogenic targets. For this reason the parametric studies described below were carried out in one dimension (1-D), with results from a two-dimensional (2-D) version of the same radiation hydrodynamics code being compared against actual experimental data from a re-entrant cone-guided capsule implosion experiment in order to give a greater degree of confidence in the results so obtained.

A major point of concern for re-entrant cone guided fast ignition is the motion of the gold that comprises the cone and its mixing with the DT fuel. In Refs. 6 and 7 Stephens describes experiments and simulations in which preheating of the gold cone causes mixing of small quantities of Au with the collapsing shell. If high-*Z* ions were to mix into the high density part of the assembled fuel, it would significantly increase cooling rates at any given temperature, stifling both ignition and widespread thermonuclear burning. The experimental results for OMEGA scale indirect drive illumination quoted in Ref. 6 showed contamination to the point where, at National Ignition Facility (NIF) scale, ignition energy requirements would be approximately doubled. In indirect drive, most of the preheating is a consequence of *M*-band (2–4 keV for Au) radiation penetrating the shell. Based on the data presented in Refs. 6 and 7 the radiant flux incident upon the surface of the cone, in an indirect drive ignition scale target, has an energy density equivalent temperature of 100 eV (meaning that the radiant energy flux is the same as

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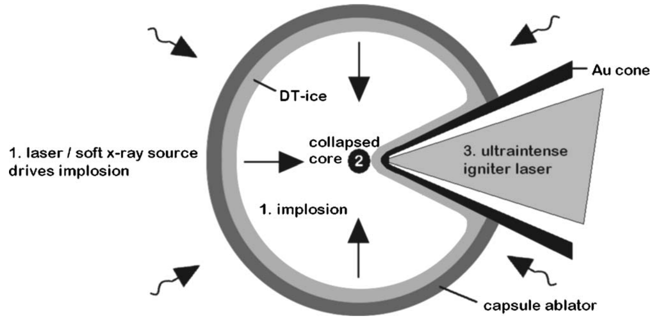

FIG. 1. Schematic of a cryogenic re-entrant cone-guided fast ignition target also illustrating the three key steps to ignition: (1) implosion, (2) the formation of a dense DT fuel core adjacent to the cone tip, and (3) the injection of the igniter laser into the cone, which results in ignition and burn in the core. Beta layering of the DT ice within the capsule will tend to result in an ice covered cone tip, as illustrated, unless some action is taken to prevent this from happening.

would be incident on an object placed in a hohlraum with a blackbody temperature of 100 eV). Data presented in Ref. 7 show that even with direct drive, harder components of the bremsstrahlung flux are still able to penetrate the shell, such that the energy density equivalent temperature of the drive is liable to be around 50 eV for an ignition scale target.

Computationally examining the mix between gold and DT under such conditions requires the application of computational resources beyond the current scope of FI work—very large meshes would be required to resolve the fine scale mixing that is characteristic of such a combination of materials. Experimental data such as that presented in Refs. 6 and 7 only allow mix to be observed by its effect on overall opacity over scales much larger than those over which mix is occurring. What is clear is that the Au vapor on the cone tip first expands and is then pushed back by the plasma pressure of the collapsing core as it nears stagnation. The interface of the Au vapor with the imploding shell is Rayleigh-Taylor unstable, and the entire outer conical surface of the re-entrant cone is susceptible to Kelvin-Helmholtz instability so the Au will tend to mix with and be entrained by the collapsing shell.

Clearly, if the motion of the gold can be constrained then the resulting mix will be limited compared to the case in which the gold is free to move. This suggests the idea of a cone tamping layer,[7] similar to that which has been proposed to control the motion of a hohlraum wall,[8] or enhance the impulse delivered to a soft x-ray driven payload.[9] The simulations presented here show that a DT-ice layer can effectively serve in this role of cone tamper. The application of a thin CH plastic or low- to intermediate-Z metal layer to the cone tip, for a similar purpose has also been suggested.[7] As will be shown below, CH plastic is in most respects a better tamper than DT ice; however, the mixing of carbon ions, or metal ions, with the fuel is clearly undesirable, and, based on the experimental evidence for Au expansion and mixing, may be unavoidable given that CH is liable to expand far more vigorously than Au. The authors suggest that an advanced fuel material such as LiDT might be a good choice for a cone tamper, and simulations have been performed to explore the viability of such a material from a radiation hydrodynamics standpoint (no thermonuclear calculations were performed in this study). It is also possible that significant radiation shielding might be added to the shell, in the form, for instance, of a high-Z layer. Such a layer can also assist in the inertial confinement of the compressed fuel[10] by adding inertial mass around the compressed core and so retarding its expansion; however, the insertion of such a layer increases the hydrodynamic energy requirements of the implosion. Insertion of intermediate or high-Z dopants into the region of the shell that is ablated can also harm efficiency by increasing the fraction of incident energy that is re-radiated.

An additional consequence of the presence of an Au cone in the capsule can be to increase the adiabat along which the ice in the shell implodes. KeV x rays falling on the gold cone heat the gold, and cause it to radiate back toward the imploding ice. Since the distribution of the photons that are re-emitted tends to be much softer than the incident flux, these photons tend to be more readily absorbed in the ice than the hard spectrum that would otherwise be incident from the opposite wall. In the case where ice, or some other low-Z material, coats the cone, such effects are mitigated by the fact that radiation from the gold tends to be absorbed locally.

One-dimensional simulations of the tamping of thick gold layers by DT ice under the influence of x-ray illumination have been performed using the multigroup radiation hydrodynamics simulation code HYADES.[11] The thickness of the tamping layer was varied from 5 to 50 μm. A total of 12 distinct x-ray drives were employed, having Planckian spectral distributions for 100 eV, 300 eV, 1 keV, or 3 keV, scaled such that the energy density equivalent temperature was 25, 50, or 100 eV. Based on the experimental data presented in Refs. 6 and 7, the drive with an energy density equivalent temperature of 100 eV and a spectral temperature of 1 keV is representative of that which the cone in a 3ω laser generated indirectly driven ignition scale capsule would experience. The 1 and 3 keV drives with an energy density equivalent temperature of 50 eV are more akin to the expectations for 1ω direct drive, with the precise spectra depending largely on shell composition. With a factor 16 less incident power than the 50 eV drives, the 25 eV drives represent heavily shielded, very large direct drive (inertial fusion energy scale) environments, or KrF laser-driven direct drive (ultraviolet illumination).

Figure 2 shows the limiting excursion of the Au-DT interface relative to t_0 for all the different drive conditions employed in our scaled Planck spectra study and for all of the tamper thicknesses investigated. Data are shown after 2 ns. Spectrally harder drives tend to deposit greater fractions of the drive energy into the Au; however, for the 3 keV drive, the energy is deposited to a significantly greater depth, lowering the energy density of the gold surface and so limiting expansion (a 3 keV Planckian peaks at 8.46 keV, at which energy the attenuation length in cold Au at solid density is ~2.9 μm). The 50 μm tamper is sometimes less effective than a 25 μm layer since, in the case of the thicker tamper, the ice near the interface may not be so effectively heated by the ionization wave propagating in from the outer surface of the tamper, so reducing the tamper pressure at the

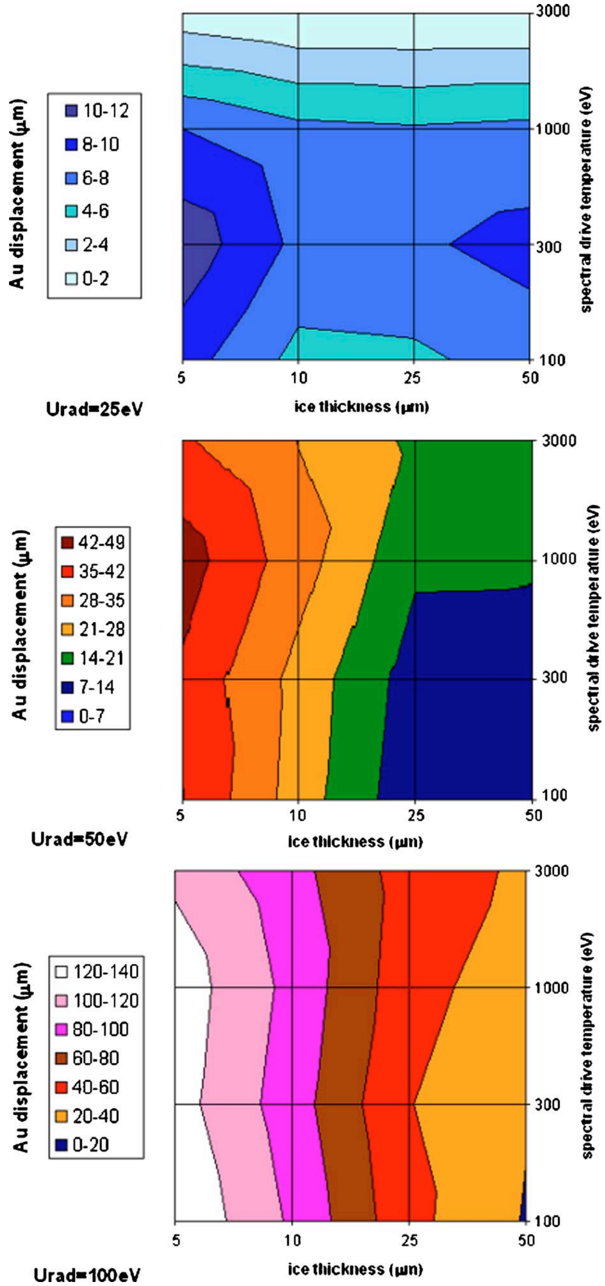

FIG. 2. (Color online) The limiting excursion of the Au-DT interface relative to t_0 after 2 ns for the various scaled Planckian x-ray drives. "Urad" is the energy density equivalent temperature of the respective drives.

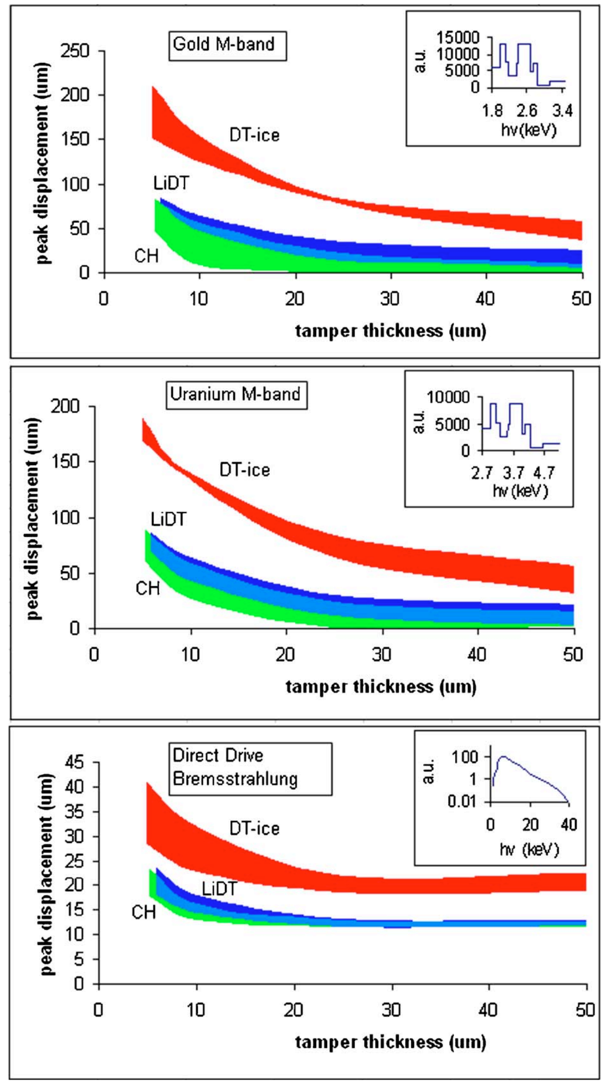

FIG. 3. (Color online) The limiting excursion of the Au-tamper interface relative to t_0 after 2 ns for the Au M-band (top right), U M-band (middle right), and bremsstrahlung (lower right) x-ray drives. Corresponding spectra are shown to the left of each figure. Data are presented as colored bands to represent uncertainties in opacity, results for CH and LiDT tend to overlap, as illustrated.

interface. This deficit is negated in the case of spectrally harder drives since here the vast majority of the drive energy is deposited directly in the gold.

Further 1-D simulations of the tamping of thick gold layers by DT ice, CH plastic, and Li(N)DT (uniform mixture of 50% LiD with 50% LiT, having a natural ratio of lithium isotopes [A(Li)=6.94]) under the influence of more realistic x-ray illumination have been performed using HYADES. The thickness of the tamping layer was varied from 5 to 50 μm. Both Au and uranium M-band drive descriptions were employed based upon data presented in Ref. 12. The M-band is the principal spectral component of the radiation from the hohlraum wall in indirect drive ICF that is able to penetrate the shell of an ICF capsule and so drive motion of the gold cone. Simulations with U spectra were performed on the basis that the cocktail hohlraums, which are now designated for a significant fraction of the planned NIF ignition scale hohlraum shots, employ an alloy that is based predominantly on U. It was considered of interest to examine whether the decoupling of the source and target M-bands would have a significant impact upon the results. Due to a lack of suitable reference data, U M-band emission was approximated by shifting the Au spectrum by the ratio of U to Au $M\alpha$ energies.[13] The energy density equivalent temperature of the drive was 100 eV in both cases, and the M-bands were each divided into ten adjacent photon groups of varying width.

Additional simulations were performed for a "typical" direct drive bremsstrahlung spectrum (low energy components have been filtered out by passage through the shell). The energy density equivalent temperature of this bremsstrahlung drive is 50 eV. This spectrum is shown, along with

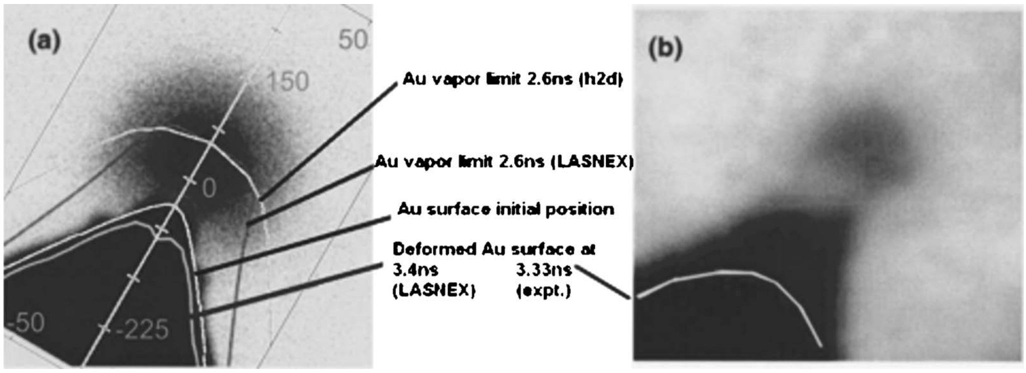

FIG. 4. (a) Simulated and (b) experimental x-ray radiographs at stagnation from OMEGA indirectly driven re-entrant cone implosion experiment as described in Ref. 6. (a) comprises a simulated x-ray radiograph generated from LASNEX data at the time of stagnation (3.4 ns in the simulation vs 3.33 ns in the experiment) as well as lines showing the original profile (h2d and LASNEX), the deformed profile (LASNEX), the position of the edge of the gold vapor at 2.6 ns (h2d), and the maximum extent of gold vapor expansion at ~2.6 ns (LASNEX).

the *M*-band spectra, and all of the associated results, in Fig. 3.

For each of the *M*-band and bremsstrahlung conditions chosen (four distinct densities for each material, for each driver spectrum) four simulations were performed to take into account uncertainties in the opacity data used by the code. Consequently, the data in Fig. 3 are represented as bands. Each band is based on the results of 16 distinct simulations. Simulations using similar opacities have been benchmarked against the Au ablation pressure scaling (time dependent),[9] which is a sensitive function of Au opacity.

It should be noted that while CH is an effective tamper, CH expands vigorously under the influence of the softer drives, and may expand far more extensively than the Au would do in the absence of tamping. This means that fuel mix with the carbon ions is liable to be an issue. In a number of the CH tamped cases the velocity of the Au boundary changes sign upon the arrival of the ionization front from the free surface, as the pressure balance changes in favor of the CH; i.e., the Au is over-tamped. The maximum excursion is reported in the figure. The final excursion is in some instances negative (the gold interface is pushed back at 2 ns relative to its initial position). In such cases, the gold mixing can reasonably be expected to extend out to approximately the point of maximum excursion.

Figure 4 shows h2d modeling of the indirectly driven noncryogenic re-entrant cone implosion experiment as detailed in Ref. 6 alongside the original LASNEX modeling performed by the second author in Ref. 6 and an experimental radiograph taken around stagnation. After 2.6 ns, LASNEX and h2d agree to within 5% as to the extent of the displacement of the Au interface away from the original position of the cone tip, toward the center of the capsule. The default local thermodynamic equilibrium average atom model for Au opacity was employed in this h2d simulation. The radiation hydrodynamics algorithms employed in the 1-D code HYADES and the 2-D code h2d are essentially identical other than in their dimensionality, so this serves as a fair "reality check."

A DT-ice layer on the surface of the gold cone in a re-entrant cone guided FI target can effectively control the expansion of the Au. DT is a less effective tamping material than CH; however, the use of such a material could lead to contamination of the imploding fuel, and hamper ignition and burn. LiDT is shown to be a useful tamping material that is less compromising than CH in this regard.

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